TO   National Academy of Sciences' Planetary Science Decadal Survey

ADVANCED TITAN BALLOON DESIGN CONCEPTS

This submission has been read by and is supported by all the individuals listed below. In addition several of them have contributed to the content.

Dr Kim Reh, Program Manager, Jet Propulsion Laboratory California Institute of Technology.

Jonathan Lunine, Professor of Planetary Science and Physics, Lunar and Planetary Laboratory

Dr David L Pierce, Head, NASA Balloon Program Office

Patricia Beauchamp, Advanced Planning, Jet Propulsion Laboratory California Institute of Technology
Tim Colonius, Professor of Engineering, California Institute of Technology
R C Downs, President Cuben Fiber Inc
Jerrold Marsden, Carl F. Braun Professor, California Institute of Technology
Don Day, President and Meteorologist, DayWeather Inc
Michael Arnold, Engineering Dept, University of California, Santa Barbara
Wade Allmon, Nott Technology LLC
Dr Dick Bohannnon, Technical Director, Bally Ribbon Mills
Dr Alberto Elfes, NASA Jet Propulsion Laboratory
Dr John Elliot, Senior Engineer, NASA Jet Propulsion Laboratory
Debora Fairbrother, Chief Technologist, NASA Balloon Program Office
Jack Jones, Principal Engineer, Mechanical Systems Division, NASA Jet Propulsion Laboratory.
Dr Jeff Hall, Senior Engineer, NASA Jet Propulsion Laboratory
Dr Greg Mungas, CEO & Chief Technical Officer, Firestar Engineering, LLC
Dr Michael Pauken, Thermal Engineer IV, Jet Propulsion Laboratory
Rob Sinclair, Chief Engineer, Airborne Systems, Space Systems Group
Luke Brooke. Tensys Dynamics Ltd
Dr David Wakefield, President Tensys Dynamics Ltd

Julian Nott

Julian Nott
President Nott Technology LLC
Santa Barbara California USA
September 15 2009

INTRODUCTION

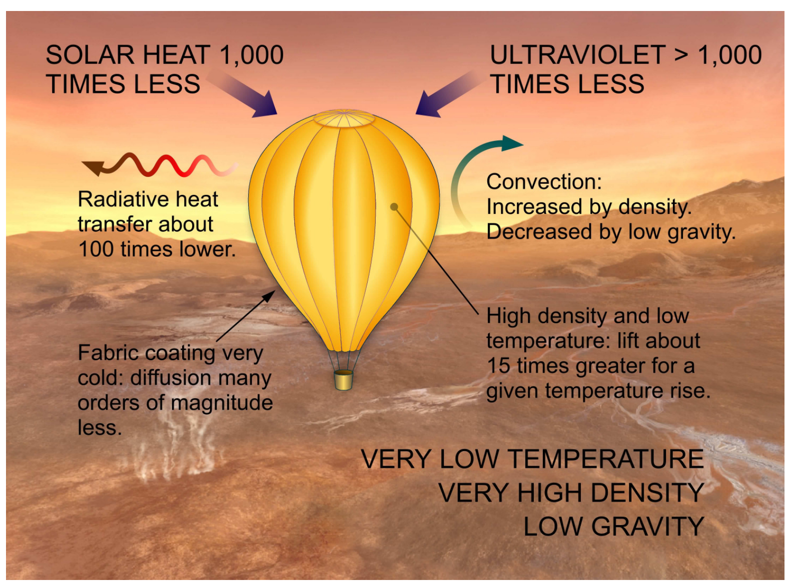
Numerous studies, including the JPL/ESA TSSM and White Papers submitted for this Decadal Review agree that Titan is of outstanding scientific interest and Montgolfiere balloons are ideal for its exploration. Extrapolated from existing balloons, these studies propose excellent designs. But Titan is so different that new concepts may allow smaller, lighter craft needing less plutonium and which can operate in worse weather. This paper examines balloon operations, weather and steering. In particular it suggests novel concepts and it is hoped this will encourage radical thinking about Titan balloon designs.

IMPORTANCE OF BALLOONS TO SCIENCE

To many people, balloons suggest luxury flights in decorative hot air balloon while sipping champagne. But balloons have had and continue to have a major role in science from the earliest days. In the 18th Century Charles and Gay Lussac, proponents of two of the gas laws, used balloons. In the 19th century they were the only way to explore the atmosphere, enabling major discoveries. In the 20th Century balloons enabled Robert Millikan and August Piccard to discover and understand cosmic rays. The first independent confirmation of Penzias discovery of the cosmic microwave background used a high altitude balloon. Balloons of all sizes are actively used in science today. Weather forecasting, central to much human activity, is only possible with data from balloons.

TITAN - THE ULTIMATE ENVIRONMENT FOR BALLOONS

Titan's thick atmosphere was first recognized by Voyager in 1980 and exploration using balloons was soon suggested. But balloons are not merely possible for Titan: it is still not always recognized that it is by far the best location in the Solar System for balloons, with conditions 1,000 times better that Earth: see diagram right. Daily changes in solar heat dominates terrestrial balloon design. Ultra-violet damage to fabric is almost as important for long duration balloons. Yet these two dominant factors are almost absent over Titan. Other factors are also mostly very favorable.



Titan's superior conditions relative to Earth.

IMPORTANCE OF WEATHER

Titan's weather is an important subject, and might provide insight into weather on Earth just as the Greenhouse Effect was first recognized on Venus. For balloons weather must be understood

from the scale of global winds carrying the balloons, to local phenomena encountered en route, particularly convective clouds. For instance it is necessary to estimate gust strength. "Gust Response" is central to aircraft design, including balloons. Topography must be considered. Work such as that of Jerrold Marsden and Claire Newman at Caltech is central. It would be invaluable to gather understanding from everyone working in this field so balloon designers can learn from meteorologists who in turn can understand what balloon designers need to know.

SEASONS AND DESTINATIONS

Titan's high latitude lakes are intriguing. But assuming they are filled by rain, the balloon might be at risk from this rain. But this might be avoided by understanding the seasons. To take a terrestrial comparison, central India has one of the world's leading scientific balloon facilities, but balloons can only be flown in winter when the weather is perfect. Flying is impossible during the summer monsoon season. Thus a simple understanding of Titan's seasons may be all that is needed to know when it is safe to fly at the lakes. Titan's seasons last 4 terrestrial years, giving time for a balloon to maneuver to suitable latitudes for each Titan season.

MONTGOLFIER VERSUS HYDROGEN BALLOONS

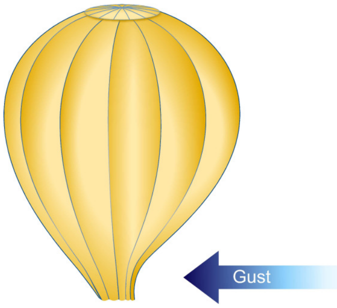
Hydrogen balloons are on order of magnitude better able to survive rain, turbulence etc. than existing hot air balloons. But they may be bought down by pinholes. It has always been impossible to avoid pinholes when balloons are packed. Considerable development has gone into systems to extract hydrogen from methane. These may well prove practical. But pinholes are insignificant to Montgolfieres and are the main focus of this paper. Heated by radioisotopes they might fly for decades. They can climb and descend indefinitely, a major advantage. This helps avoid bad weather, see notes about steering below, offsetting one major advantage of hydrogen balloons.

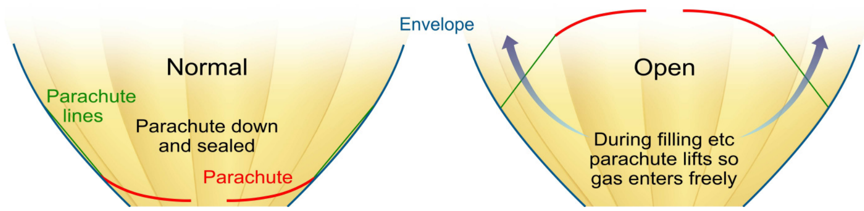
IMPROVING MONTGOLFIERES

One reason hydrogen balloons survive weather better is that the base opening is much smaller, see pictures right. The mouth of a conventional hot air balloon must be large for inflation and to separate the fabric from the burner. This is a disadvantage since, when hit by a gust, air is easily driven out of the mouth, loosing lift. Cold air immediately refills the balloon, exacerbated the problem.

But a Titan balloon only needs a large mouth during inflation: in flight there is no flame. The gust problem might be largely eliminated using a fabric parachute functioning as a check valve, see schematic on the next page. This base parachute mimics the extremely reliable crown parachute universally used in sport hot air

balloons. It reduces the advantage of a hydrogen balloon in surviving gusts. It is a good example of how Titan's different circumstances invite the application of very novel concepts.

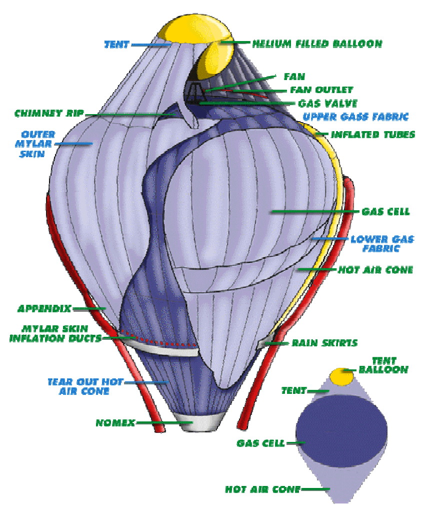




ADVANCED BALLOON CONCEPTS

The other reason hydrogen balloons survive weather better is because the lift per unit volume is larger making it more resistant to gust.

Can a hot air balloon be improved in this regard? And will it be beneficial in other regards? Multiple-layer balloons have been built, see illustration below. But in most craft the envelope is the most costly element and the added complexity yields modest benefits. But complex envelopes are justified in special situations such as a solar balloon where the heat supply is limited and a complex envelope is essential. Tens of millions of dollars were spent on attempts to fly around the world so costly multi-layer envelopes were justified. For Titan, more than perhaps any project, the envelope will be a tiny part of the total cost and complex envelopes may be fully justified.



1974 double layer test **1981 double layer solar** **1999 multi layer Breitling world flight**

For short flights cheap hydrocarbon fuels provide heat rapidly. In contrast plutonium is scarce and expensive so complex envelopes may well be justified for Titan.

DRAMATICALLY DIFFERENT – A TITAN BALLOON WITH TEN LAYERS

But if a complex envelope is to be used, why stop at two layers? Why not use many layers to greatly reduce heat loss? How well would a balloon with ten-layer envelope function?

10,000 meters altitude	84K ambient	3.3 Kg/ cubic meter	6 m internal diameter
Outer fabric 17 gsm	9 inner layers 10 gsm	Conductivity ratio 2	7 m external diameter
Payload 100 Kg	ASRG 22 Kg	Envelope 12.3 Kg	Lift temperature 139K
Heat Loss 213 Watts	***ASGR heat 360 Watts, a substantial surplus***		

Fabric weights are from the next section. It is uncertain how effectively the gas will insulate. Trapped-air insulation approaches the conductivity of air. This table assumed the gas has 2 times the conductivity of nitrogen at the relevant temperatures. If this is optimistic, use twenty layers or a larger separation: the envelope is a small part of the total mass. This heat could be provided by a singe ASRG. The advantages are obvious, a lighter craft requiring less plutonium.

Is this practical? Professor Colonius at Caltech is developing CFD models of Titan heat transfer. [See for instance D. Appelo, T. Colonius, J. Nott, and J. Hall. Computational Modeling and Experiments of Natural Convection for a Titan Montgolfiere. AIAA Paper 2009-2806.] His numerical models will allow preliminary investigation of a wide range of ideas. Promising concepts can be tested quickly, at low cost, in a facility like the Titan Sky Simulator, below. If the suggestions made here are flawed, the combination of numerical and practical testing may soon lead to effective concepts. And explaining the general needs to the balloon community at large may elicit creative suggestions.

NOVEL FABRICS AND CONSTRUCTION

In recent years major advances have been made in fabrics driven by competitive sailing, large building components and aerospace, for instance extensive use of composites in the Boeing 787. While too complex for wide use in terrestrial balloons, such fabrics may be invaluable for Titan.

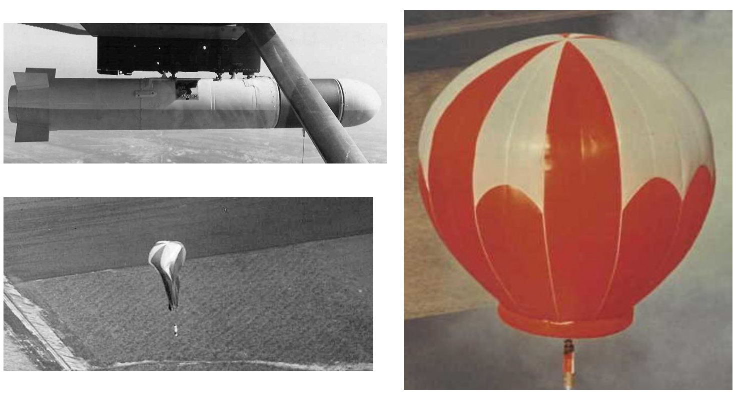
Two particular developments might be useful. The first is 3D Weaving, for instance developed by Bally Ribbon Mills. In conventional composite structures, separate layers of fabric are held together by resin so delamination is possible. With a 3D Weave, filaments run continuously through different layers, avoiding delamination and reducing weight. 3D Weaving might be very effective for creating a multi-layer lightweight "quilted" balloon envelope.

Another company making major advances is Cuben Fiber. They construct fabrics by laying threads on plastic substrate. The fibers are straight so crimp is eliminated and strength approaches the ultimate fiber strength. Layers can be added in different directions or locally so strength is only where needed. Cuben can engineer materials as light as 17 gsm suitable for the outer envelope and even lighter fabric for the inner layers, which only prevent gas circulation. They suggest that using 3D fabric components curved in two dimensions will give considerable payoffs, allowing fewer parts and lighter weight: lighter fabrics are often better than heavy material at surviving folding damage.

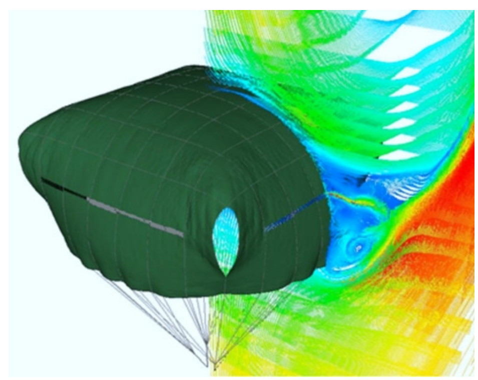
Constructing a multilayer Titan balloon will be simple compared to these craft. Each one is a certified passenger craft and retains its shape ONLY from internal pressure. Note the remarkably complex details achieved with fabric and the passenger baskets which give scale.

BALLOON LAYOUT

The radioisotope heat source might be placed in the balloon envelope to ensures that all heat generates lift. But with a highly insulated balloon wasting some heat is less critical. If the heat source is integral with the main gondola all the heavy components are a single unit: heat could be carried up via heat pipes or convection. Systems like “Top Hat” with mass in the envelope have never been popular. Gust behavior is not compromised and the instrument section kept warm. With no heavy object in the envelope, the balloon can fill simply by dropping through the atmosphere: this has been proven with battlefield flares used in combat, see picture below.



Free-fall deployment of balloon for battlefield flare.
Photos Rekwin Archive



FSI, is useful. It is show here for a parachute. Image Airborne Systems.

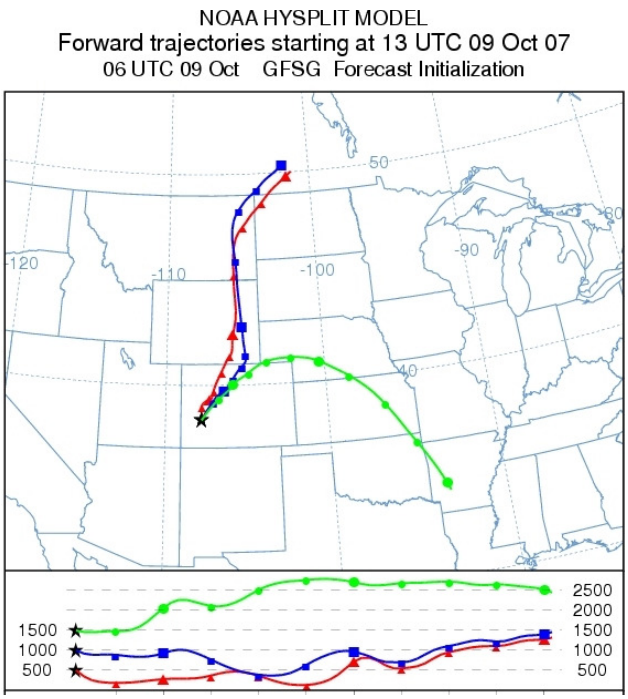
BENEFITS OF SMALL BALLOONS

These proposed ideas lead to substantially smaller balloons needing less plutonium. Smaller volume gives higher internal pressure and smaller displacement, both beneficial in gusts: more robust designs give greater operational flexibility. A smaller balloon is more easily moved by propellers. There is a shorter path if a heat pipe is used to carry heat into the envelope

RAPID HEAT GENERATION

All terrestrial experience shows it is impossible to fly a hot air balloon without a burner to generate heat quickly to avoid obstacles. A Titan balloon may need a rapid supply of heat for instance in a gust and by definition explorations leads to unexpected events. For modest corrections is may be possible to store sensible heat from the radioisotopes or electric power. An idea source of larger amounts of contingency heat may be the monopropellant systems being developed by Firestar Engineering to replace hydrazine thrusters.

OPERATIONS AND STEERING



A forecast of good condition for long-distance steering.

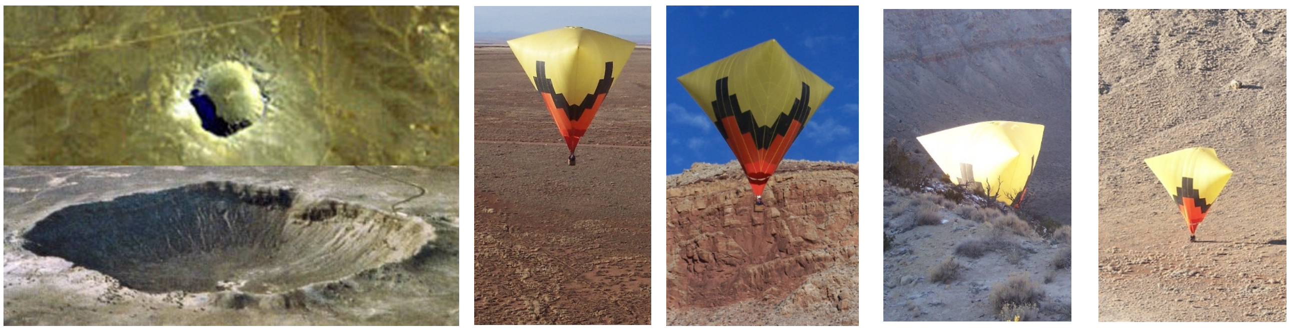
Autonomous steering over 10 kilometers

Steering balloons by rising or descending into favorable winds is highly effective for terrestrial balloons. Balloons cannot go anywhere, but can achieve surprising control within the general flow. At the largest scale, using forecast models, pilots regularly cross continents and oceans. At the smallest scale, using only on board GPS wind data, pilots flying autonomously routinely achieve accuracies of a few meters after traveling ten kilometers. In the photo, above right, note the marker dropping and markers near the target. Caltech [Marsden, Karol, Nott] is currently studying how pilots achieve this accuracy: and conclusions could be tested using autonomous CMET balloons. All terrestrial experience shows that there is more variation in wind direction than any forecasting model shows. A Titan balloon could steer to reach scientific goals and avoid bad weather. A LIDAR able to detect winds even a few hundred meters from the balloon would be greatly enhance its ability to fly autonomous. With a transparent atmosphere full of tholin particles, Titan appears to be ideal for LIDAR.

Another possibility is propellers to push the balloon sideways. They add little weight and if they fail, the mission is not lost. Even if the balloon only moves slowly, in Titan's anticipated light wind, they could be invaluable.

FLYING NEAR THE SURFACE

While it may not be wise for a balloon to land, assuming Titan has light surface winds, there should be no reluctance to fly low and use wind steering to reach goals. Balloon pilots frequently delight in "contour flying", following the surface, as the pictures below show. The benefits of close up examination of the surface are obvious. And scientifically interesting Titan materials are likely to accumulate in depressions and valleys. Flying very low the gondola often touches the ground and this is quite harmless. Any Titan gondola should be designed to survive ground contact at perhaps 2 meters per second.



Exploring a geological site, the Barringer Crater, AZ. Left from orbit [Landsat] or an aircraft. Sequence shows a balloon approaching the crater, descending and landing to sample. Balloon photos courtesy Keith Sproul.

THE TITAN SKY SIMULATOR™

JPL has funded the Titan Sky Simulator™. Data has been collected from a balloon flying at ***minus*** 170C. Initial operation shows that even at this temperature qualitative behavior, such as shape during inflation, mimics conventional balloons up to 50,000 times larger in volume. This suggests that 40 years collective experience with conventional hot air balloons can give useful insights into Titan balloon behavior.

Titan Sky Simulator ™ and view down on balloon flying at *minus* 170C.

CONCLUSION

Titan is an outstanding scientific goal, balloons are an ideal way to explore and it is hoped these concepts may improve Titan balloon design. Allowing substantially smaller balloon may allow two balloons to be sent on a mission where one was originally planned!